Constraint-based planning

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Outline

Motivation

- NASA planning needs
- Project goals

Technical basics

- Motivation for approach
- Brief introduction to constraint-based planning

Applications

- Research projects
- Mission-related projects

Need for advanced planning

NASA needs for autonomous planning capabilities

- Ground-based assistance with spacecraft operations planning
- Automated decision-making on board spacecraft
- Air traffic management assistance
- Complex operations, such as flight planning

Common elements of domains

- Concurrent operations with temporal dependencies
  - Instruments, mobility, heaters, communications, etc.
- Limited resource availability
  - Power, data storage, equipment, etc.
- Complex rules for interactions between operations
  - Example: Instruments require heating, interact with communications and mobility operations

Project Objectives

High-level goals of CBP project

- Develop plan representation and reasoning techniques
  - Capabilities to support NASA applications
  - Well-defined algorithms and theory
  - Support different search methods and mixed-initiative planning
- Build core planning system
  - Foundation for current and future research work
  - Core representation and reasoning module for applications
- Apply and adapt techniques to applications
  - Work to understand application needs for core capabilities
  - Work with research and mission projects to apply technology

Motivation and heritage

Handle planning in the real world

- Real-world activities have temporal extent
  - Example: Slew spacecraft from one target to another
  - Time is continuous and relations are quantitative
- Real-world activities require resources
  - Example: Imaging requires available data storage
  - Resources may be single or multi-capacity, reusable or consumable
- Real-world plans have complex concurrent interactions
  - Example: High-resolution imaging cannot be done while spacecraft is thrusting, and only if imager is warm enough

Approach based on earlier systems

- HSTS - core of Remote Agent Planner (flew on Deep Space One)
- IxTeT - handles time and resources - similar to HSTS
- Descartes and other systems have used constrained variables

Extend actions and fluents to intervals

Temporal extent of actions and fluents

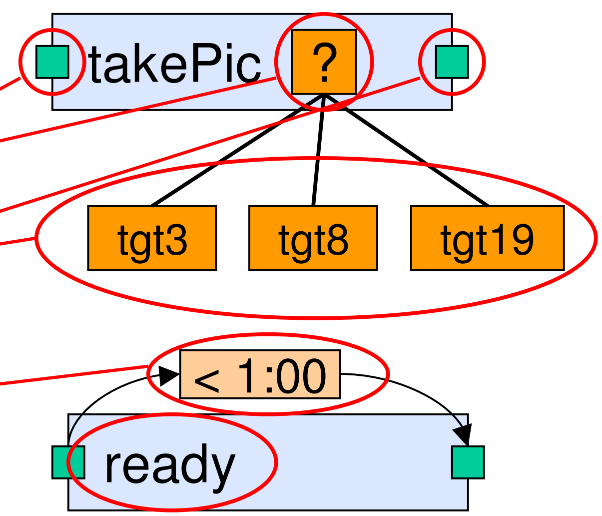
- Actions have durations
  - Taking image takes time
- Fluent values may expire
  - Ready for limited time after warm-up

Use predicates to describe both

- Predicates with variable arguments enable delayed commitment

Interval describes predicate over time

- Predicate with variables taking values from domains
- Start and end time
- Duration restrictions



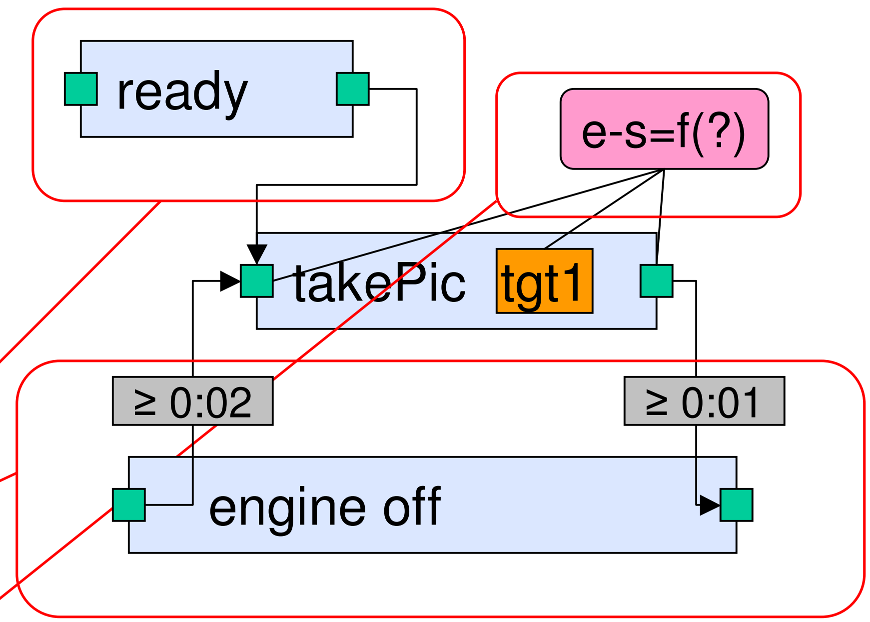
Planning domain constraints

Planning domain

- Predicate types
- Domain constraints

Planning constraints

- Specify conditions for intervals appearing in plan
- Examples:
  - Camera ready before takePic
  - Engine off from 0:02 before takePic to 0:01 after
  - Duration of takePic depends on target



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Reasoning techniques

Dynamic constraint reasoning with procedures

- General framework for representing plan candidate constraint network and perform constraint reasoning such as propagation

Reasoning with uncertainty

- Extend temporal and constraint reasoning to handle uncertainty in time and other parameters

Reasoning about resources

- Compute and use resource bounds for plan candidates

Search techniques

- Support different search control for modifying candidates

Intelligent search control

- Simplify use by reducing need for hand-crafted heursitics

Projects using EUROPA

IDEA

- Use planning system to uniformly represent future plan, execution plan, and execution results

SOFIA

- Use plan database to represent complex flight plans that include observation arcs, endurance limitations, etc.

EOS

- Use plan database to represent observation requests and schedules for multiple Earth-observing satellites

Spoken dialog interface to planning

- Link plan database and planning capabilities to a spoken dialog interface to provide easy access to plans and planners

Projects using EUROPA

Personal Satellite Assistant

- Using planner and IDEA to build a controller for PSAprototype, an autonomous satellite with sensors and motors to operate on International Space Station

Mars Exploration Rovers (Mars 03)

- Use plan database to represent science and engineering activities, linked to APGEN visual interface
- Use planning with non-chronological goal rejection to provide mixed-initiative plan completion
- Extend planner to use APGEN-generated resource profiles to generate plans within resource bounds

Selected Publications

- Jeremy Frank, and Ari Jonsson, “Constraint-based Attribute and Interval Planning”, in Constraints Journal special issue on planning.
- David Smith, and Ari Jonsson, “The Logic of Reachability”, in AIPS 2002.
- Paul Morris, Nicola Muscettola, and Thierry Vidal, “Dynamic Control of Plans with Temporal Uncertainty”, in IJCAI 2001.
- Ari K. Jonsson, and Jeremy Frank, "A Framework for Dynamic Constraint Reasoning using Procedural Constraints", in ECAI 2000.
- Jeremy Frank, Ari K. Jonsson, and Paul H. Morris, "On Reformulating Planning as Dynamic Constraint Satisfaction", in Symposium on Abstraction, Reformulation and Approximation (SARA), 2000.
- Ari K. Jonsson, Paul H. Morris, Nicola Muscettola, Kanna Rajan, and Ben Smith, "Planning in Interplanetary Space: Theory and Practice", in AIPS 2000.
- David E. Smith, Jeremy Frank, and Ari K. Jonsson, "Bridging the Gap Between Planning and Scheduling", Knowledge Engineering Review, 15(1), 2000.
- Ari K. Jonsson, Paul H. Morris, Nicola Muscettola, and Kanna Rajan, "Next Generation Remote Agent Planner”, in iSAIRAS 1999.

Extra slides

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Dynamic constraint reasoning

Framework for dynamic constraint reasoning

- Supports arbitrary procedural constraints
  - Specialized reasoning for declarative constraints supported
- Performs propagation to eliminate values and check consistestency

Properties

- Combinations of correct elimination procedures proven to also be correct
- Baseline propagation performs a version of arc consistency maintenance; achieves AC if each procedure achieves AC
- Performance incomparable to declarative arc consistency methods; each constraint faster, propagation cycle slower

Reasoning with uncertainty

Temporal uncontrollability

- Certain events may not be under planner control
  - Actual event time decided during execution
- Example: How long it takes to move to a target
- Need methods to build plans that will work regardless of outcome of uncontrollable event

Tractable uncertainty reasoning

- Uncertainty in outcome requires universal quantification
- Solvable constraint networks allow any outcome to be extended to a solution
- Preliminary work underway on identifying and using solvable constraint networks

Resource reasoning

Bounding resource usage

- Flexible candidate plans give rise to bounds on resource use
- Need to calculate tight bounds to identify resource problems early, and provide guidance to search engine

Using external resource calculations

- In a current application, resource calculations provided by external simulation software
- Simulation only provides earliest start time resource profile
- Adapt search to reason with provided profiles

Combining resource reasoning and mutual exclusion

- Uses critical path and mutual exclusion analysis to propagate integrated resource bounds
- Ongoing work in collaboration with summer students

Bounding resource usage

Using maximal flow to calculate tight bounds

- Given a temporal network of resource use events, determine max/min resource use at a given time T
- Identify events that can be ordered with respect to time T
- Build flow network from events and resource use
- Maximal flow calculations provide resource bound
- Bounds are provably tight

Ongoing work

- Theoretical results and algorithms in place
- Incorporation into planning framework and performance tests to be done in near future

Search techniques

Support for multiple search methods

- Dynamic enforcement of domain constraints
- Subgoal intervals and variable sets may become obsolete when later changes are made
- Constraint database currently maintained in consistent form, to support propagation
  - Efforts underway to support queries into inconsistent database

Currently used search methods

- Chronological backtracking
- Mixed-initiative planning
- HBSS
- Non-chronological backtracking with goal rejection

Heuristic search control

Language for specifying heuristics

- Based on language used in Remote Agent Experiment
- Uses priority assignments for variables and subgoals
- Supports limited context specification

"Values remaining" inspired heuristics

- Evaluate flexibility of decision points and decisions

Projected state space analysis

- Project state space onto subset of states to guide search
- Have method to build projected state space approximations

Mutual exclusion reasoning for time

- Extend mutual exclusion reasoning to temporal planning
- Allows pruning candidate plans

Deliveries and schedules

Software deliveries

- Ongoing support for needs of collaborative efforts
- Improved performance of core software

Research milestones

- Planning with resource bound calculations
- Reasoning about uncertain outcomes
- Domain-independent search control

Schedule outline

- FY01: Initial use in application prototypes
- FY02: Prototype implementation of reasoning modules for resources and uncontrollable events; improved performance; continued deliveries for applications and research
- FY03: Prototype implementations of domain-independent and automatically generated search control information; continued development for applications